Normal Paper

Metop-C Deployment and Start of 3-Satellite Operations

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Abstract

Metop is the space segment of the EUMETSAT Polar System (EPS), which provides real time data to several European meteorological services as well as to NOAA and other international agencies. The third Metop satellite, Metop-C, was launched on the 7th of November 2018 and shall enter in operations in few months, once the on-going commissioning of the meteorological products is completed. Each Metop satellite was designed to survive at least five years; to achieve the target mission duration of 15 years a sequential deployment of the satellites was foreseen, replacing an old one at end of life with a newer one; thanks to the excellent performances of the launchers and of the platform itself, and to continuous improvements to the fuel management, it was possible to extend the operational life of each satellite by a factor three, still maintaining enough fuel to perform safe de-orbiting operations (foreseen for Metop-A, launched in 2006, at the end of 2021). That provided the opportunity to develop in 2012 (after Metop-B launch) dual-satellite products, which now, with the arrival of Metop-C, can be evolved to tri-satellite; several decisions, concerning the selection of launch date and time as well as commissioning and operational locations, had to be been taken to achieve the target configuration; the analyses leading to these decisions are discussed here.

Keywords: Mission execution, Launch and Early Operations Phase.

Introduction

The first two Metop satellites (A and B) where launched, respectively, in October 2006 and September 2012, by Soyuz/Fregat launchers from the Baykonur Cosmodrome in Kazakhstan. For the third one, Metop-C, the same type of launcher was selected, but the launch operations were carried out, in November 2018, from the Kourou Space Centre in French Guyana.

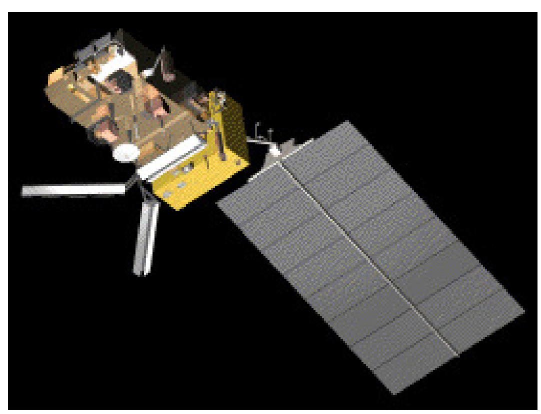

Fig. 1: The Metop satellite

All the satellites of the Metop family (shown in Fig. 1) are operated into a Sun-synchronous repeat orbit with the following characteristics:

- Local Time of the Descending Node (LTDN) of 9:30, with +/-2 minutes of tolerance;
- Repetition cycle of 412 orbits in 29 days, within 5 km from the nominal ground-track;
- Eccentricity kept close to the frozen value, with deviation below 0.0002.

After its launch Metop-B has been positioned on the same ground-track as Metop-A, to ensure identical views from the two satellites, and at the same time as separated as possible in orbital phase, to maximise the daily coverage with the optical instruments.
As on a repeat cycle of 29 days only 28 locations, separated by integer numbers of 1/29 of an orbit, fulfil the first condition, a nominal separation in phase of 14/29 of an orbit was implemented (as shown in Fig. 2).

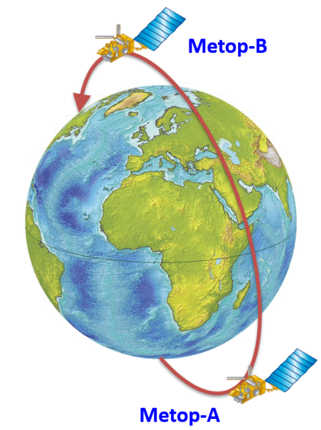

Fig. 2: Dual-satellite Metop nominal configuration

After 10 years of operations on Metop-A inclination maintenance was suspended in 2016, to save enough fuel for End of Life operations (as described in [1] and [2]), in line with the ISO 24113 Space Debris Mitigation guidelines; as a consequence its LTDN started drifting toward early morning local times and, being the ground-track still maintained (little fuel is needed), the separation in phase with Metop-B started reducing significantly (as depicted in Fig. 3).

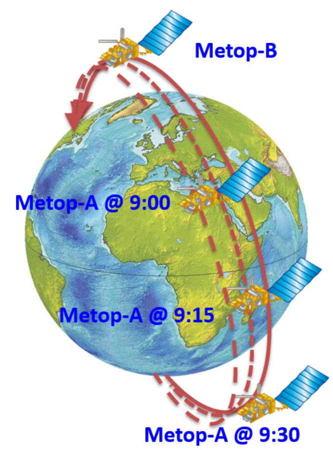

Fig. 3: Metop-A relative phase evolution with LTDN drift

Therefore, at the time when Metop-C has to be launched, the in orbit configuration of the other two Metop satellites was not anymore the nominal one and was, moreover, still evolving in time; that had to be taken into account when consolidating the strategy for first launching, then commissioning and finally exploiting the new satellite.

Metop-C launch time (and date) selection

As mentioned above, the launcher selected for Metop-C is a Soyuz/Fregat launcher. Its trajectory is invariant in the Earth-fixed reference frame. Therefore the in-orbit position (PSO) at separation is always the same, regardless from the date and the time of the launch itself (PSO=216 deg, time between launch and separation: 3618 seconds).

Consequently, the achieved LTDN is only function of the launch time, regardless of the launch date; that permits to select the launch time to achieve an optimal initial LTDN, which, together with an adequate bias in the initial inclination, permits to implement a first long fuel-neutral (12 to 18 months) LTDN cycle within the +/-2 minutes window; for the first two Metop satellites the inclination at launch was biased with respect to the nominal value by 35 millidegrees and its LTDN by -70 seconds; the Metop-B case, for which no inclination correction was needed during LEOP, is presented in Fig. 4.

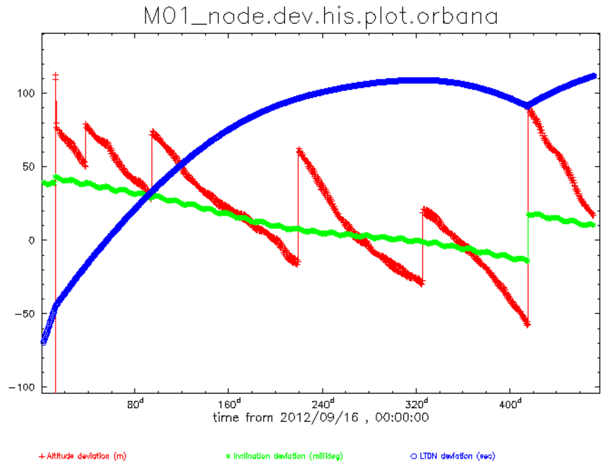

Fig. 4: Metop-B LTDN deviation after launch

It can be observed that more than one year of LTDN cycle is directly implemented by the launcher, without need of any inclination correction.
The requirement to maintain the LTDN deviation within +/-2 minutes from 9:30 (so in the window [9:28, 9:32]) comes from the need of Sun signal into the calibration port of the GOME instrument (as explained in [3]); however, close to the Autumn equinox it can be observed that, due to the Sun displacement from the mean value induced by the time equation, a violation of the lower boundary can be tolerated.
On Metop-B a 30 seconds violation around the Autumn equinox 2018 was therefore implemented, to permit postposition of the routine inclination corrections to a more efficient date (more details can be found in [4]), with no impact at all on the GOME calibration.

For Metop-C, the Metop-A experience was used to optimise even further the initial launcher conditions; these are selected in order to:
- minimise the probability of having to perform an inclination correction in LEOP (required if the LTDN evolution would lead to a violation of the acceptable margins in the first 45 days after the launch, not to affect negatively the initial operations on the scientific instruments);
- maximise the probability of achieving a long (more than 1 year) LTAN cycle without requiring any inclination correction during the entire period.
Being the launch date close enough to the Autumn equinox, it was possible to extend the target LTDN window to [9:27:30, 9:32]; that lead to a selection of an initial LTDN with -90 seconds offset (instead of -70 seconds), and to a launch time of 01:47:27 UTC.

Fig. 5 presents the expected short term LTDN evolution for a very large inclination error of 95 millidegrees and of -70 millidegrees, coupled with an equivalent (in terms of number of sigma of the nominal launcher performances) error in initial LTDN (its initial value is also corrected to consider the effect of the phase drift needed to achieve the target position); no violation of the extended LTAN window is observed in the first 45 days (not true for the nominal one).

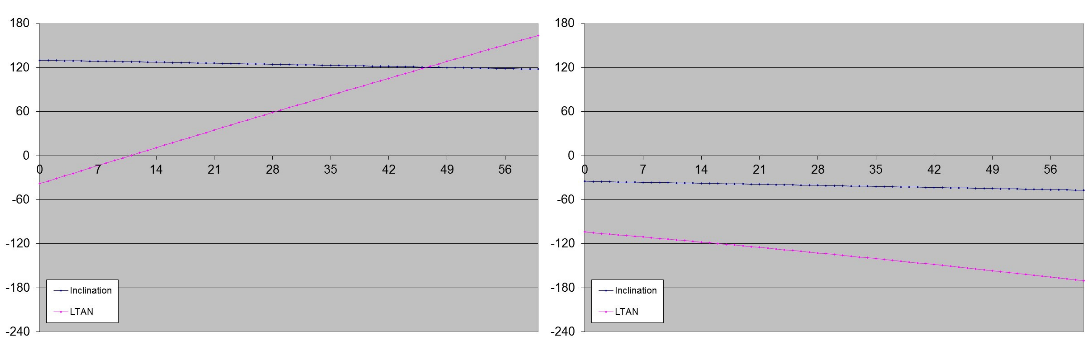

Fig. 5: Expected Metop-C LTDN deviation after launch for large injection error cases

Considering that the contractual 1 sigma performance in inclination of the launcher is 40 millidegrees, but the expected one is around 30 millidegrees, the probability of having to execute an inclination correction in LEOP is minimal; only positive corrections are expected, which are then in the optimal direction to implement a long LTDN cycle.

Even if no inclination correction is performed during LEOP, it is necessary to make sure that the LTDN can afterwards be kept safely within the operational margins; in particular, in case of large negative inclination error the LTDN error has to be brought back within the nominal window (so over 9:28) before mid-February, when the most critical geometrical configuration for the GOME calibration are observed; a correction of 80 millidegrees is required 45 days after the launch to ensure that, just within the capability of the platform in routine operations through 2 burns (Fig. 6).

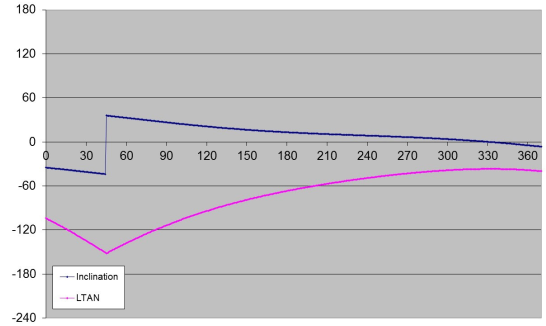

Fig. 6: Expected Metop-C LTDN deviation after launch for large negative injection error plus correction at extended window limit

Very interesting is also the case very large positive inclination error; to avoid violation of the nominal LTND window 45 days after the launch a huge correction of -110 millidegrees would have to be implemented; such a correction can be implemented by the Metop-C satellites only though 3 burns; even if feasible, the complexity linked with that operation would lead to consider advancing one of the burns to the LEOP (many thanks to ESOC for accepting that strategy); these cases are observed for inclinations error above 75 millidegrees, still quite unlikely (Fig. 7).

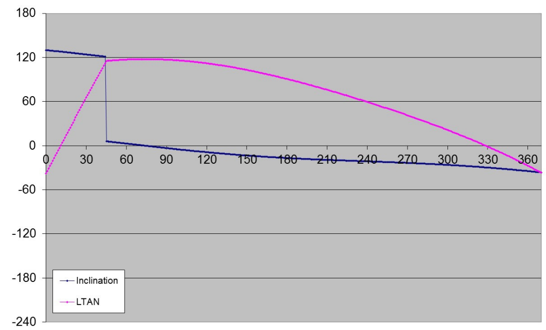

Fig. 7: Expected Metop-C LTDN deviation after launch for large positive injection error plus correction at nominal window limit

Fig. 8 presents the expected short term LTDN evolution for a moderate inclination error of 13 millidegrees and of -13 millidegrees.

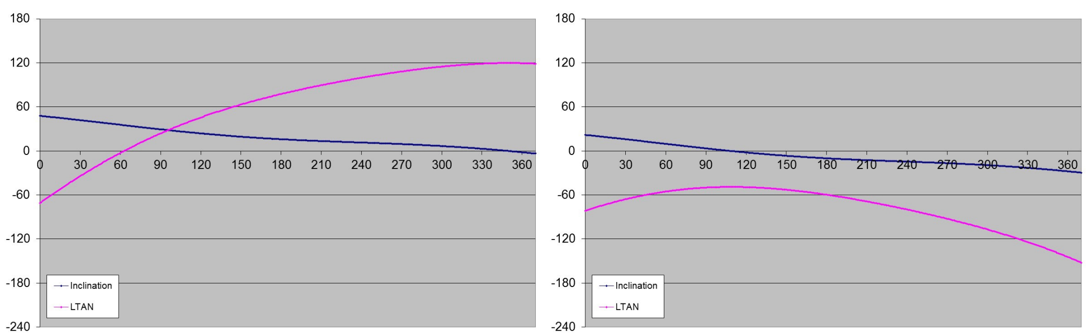

Fig. 8: Expected Metop-C LTDN deviation after launch for moderate injection error cases

It can be observed that a long LTDN cycle (of one year for a negative inclination error, considering the extended LTDN window; for nearly the double for a positive one) is implemented; that means that in around 30% of the cases (assuming 30 millidegrees of launcher dispersion) no inclination correction at all is needed in the first year of mission (on the first two Metop launches, the observed dispersion was well below these values).

It is therefore evident that the selected initial conditions fulfil the optimisation criteria described at the beginning of the paragraph.

Another consequence of the fact that the in-orbit position (PSO) at separation is always the same, regardless from the date and the time of the launch itself is that the relative position with respect to the other two flying Metop satellites changes every day; as the launch altitude selected for Metop-C is 16 km below the nominal value, leading to an important relative orbital drift, on certain dates Metop-C satellite may experience, in case of autonomous entry in contingency mode, interferences in radio-frequency (RF) with an operational Metop satellites during the initial, critical LEOP phase.

That would result in an unacceptable risk for both satellites and these dates are to be excluded from the candidates for launch. It is also possible to identify several dates (among which the 7 November) where interferences may happen during the first two days of LEOP; these dates are acceptable for launch, but special care is needed to mitigate the resulting interferences. Further details on how these dates are identified and on the special operations implemented to cope with them can be found in another paper presented in this conference (see [5]).

Metop-C commissioning location selection

The commissioning location of Metop-B was specified to be on the same ground-track of Metop-A (to permit a 1 to 1 comparison of the images taken from very similar positions in the sky, even if on different dates) and with a separation in orbit as large as possible.
As already explained, only 28 orbital locations, defined as Legs, permit to overfly the same ground-track of Metop-A; Metop-B was therefore commissioned on Leg-14 wrt Metop-A (which is then on Leg-15 wrt Metop-B, as shown in Fig. 9, where all Legs are also identified).
The same was foreseen for Metop-C; however, as Metop-A is still in good shape and its contribution still appreciated, it was decided to keep it in operations well over the expected lifetime (as explained in [1]).

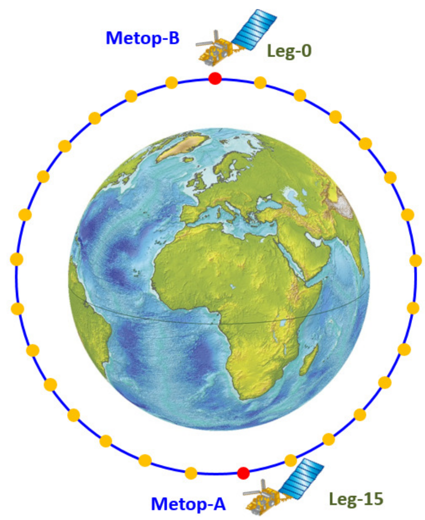

Fig. 9: Metop-B commissioning location with respect to Metop-A

That makes impossible to adopt for Metop-C the Metop-B strategy, as the target location is not free; it is important to keep in mind that, while during LEOP and initial SIOV activities it is acceptable to have a dedicated ground station for the operations of Metop-C, the same ground station shall be used to operate the three satellites during commissioning; on another hand, due to the drift in LTDN observed on Metop-A (more than 13 minutes at the launch date of Metop-C), its on-orbit position changed enough to leave sufficient place to position Metop-C between Metop-A and B, as shown in Fig. 10.

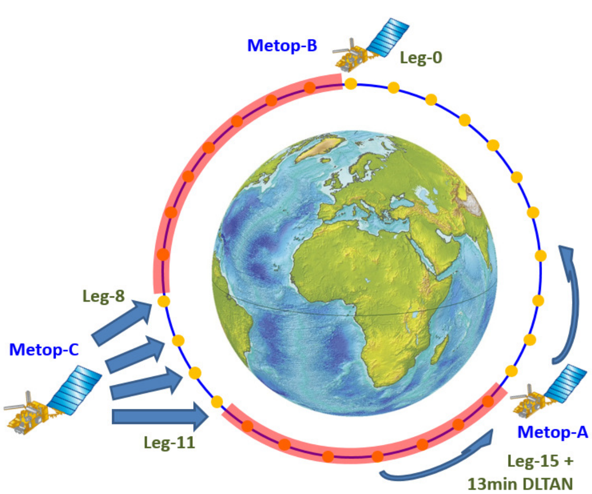

Fig. 10: Metop-C possible commissioning locations

As it can be observed, enough separation has to be present to ensure that consecutive passes can be taken with the same antenna; the following was considered when computing that minimum separation for Metop-B and Metop-C:
- up-to 8 minutes are need after LOS (loss of signal) of one satellite to be ready to acquire the next satellite at AOS (acquisition of signal);
- a pass can last up to up-to 15.5 minutes (with AOS and LOS at 0 degrees elevation);
- each satellite can move wrt its nominal location up to 2 minutes (LTDN control window).

Therefore a minimum separation of 27.5 minutes is needed; that implies that the 7 legs before and after Metop-B (one Leg corresponds to around 3.5 minutes) cannot be considered.
For Metop-A less margins are needed on what concerns the LTDN window, as its separation wrt Metop-C after launch is well known and increases in time; that, together with the displacement of nearly 4 Legs due to the LTDN drift (and correlated drift in phase as the ground track is maintained), permits to release 4 possible Legs as commissioning location: 8, 9, 10 and 11.
It is worth notice that, considering the above mentioned values for maximum pass duration and maximum time required between consecutive passes (LOS to AOS), it would have not been possible to find any compatible location if LTDN control on Metop-A was maintained.

Target 8 was excluded as the available margin of 0.5 minutes was considered unsatisfactory to ensure robustness against second order effects, such as the displacement of each satellite in the ground-track and the change in time between ascending node (ANX) and AOS due to the difference in time of crossing of the ascending node (due to the Earth rotation); among the remaining 3, the main criterion for the selection of the optimal one was the operational robustness of the acquisition strategy and consequently of the LEOP operations.

As explained in [5], the displacement to be implemented between the separation location and the commissioning location changes for any launch date (in the 29 days of the repeat cycle); moreover, acquisition of the commissioning location shall be ensured within 7 and 18 days after launch, due to constraints in the initial instruments' operations (switch-on before, de-contamination after); therefore during LEOP it may be necessary to adjust the satellite altitude to ensure that.

It can be observed however that if the satellite is very close to the target location when the first LEOP manoeuvre is implemented (normally 2.5 days after launch), it may be very nearly impossible to acquire it safely, as clearly depicted in Fig. 11; the altitude change needed to acquire the first target in 6 days is so large that the proportionally large execution error may not permit to achieve it within the desired time window.

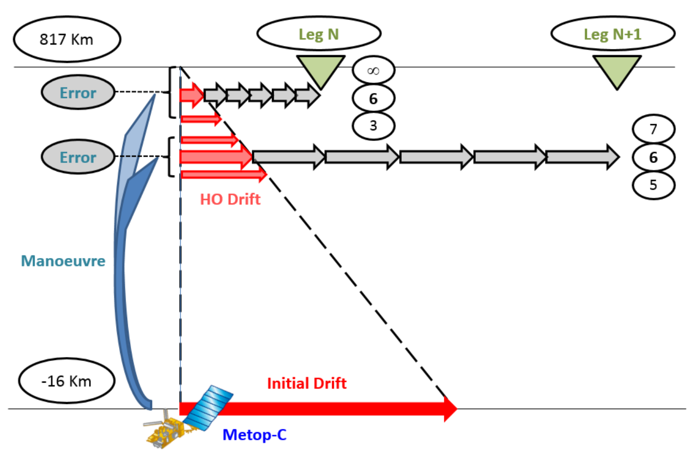

Fig. 11: Metop-C acquisition on first target

On another hand, if the following target is selected, the required correction is smaller and then the correlated execution errors; their impact in the achieved (larger) post manoeuvre drift, and thus in the time to target acquisition, is therefore relatively small. A similar scenario can be envisaged if the satellite, at the time of first manoeuvre, is located between Leg N and Leg N+1; in that case acquisition of the Leg N-1 with drift reversal is the most robust option.

The only target that permits to implement that robust acquisition strategy is therefore Leg-10, being Leg-9 and Leg-11 available in case of excessive proximity to Leg-10.

Metop-C operational location selection

The natural location for Metop-C operations would be in opposition with Metop-B (around half orbit apart), to ensure continuity of data on the dual mission; the original plan was to move Metop-C at the end of the commissioning, in spring 2019, on Metop-A initial nominal location (on Leg-15) as soon as Metop-A LTAN drift would have reached around 24.5 minutes (corresponding to 7 legs of phase drift) and implement then the so called Trident configuration, depicted in Fig. 12.
At this point Metop-A would be kept on fixed relative phase wrt the other two Metop satellites at around Leg-22, having to abandon however the ground-track control (as LTAN drift would continue, causing a displacement toward East).

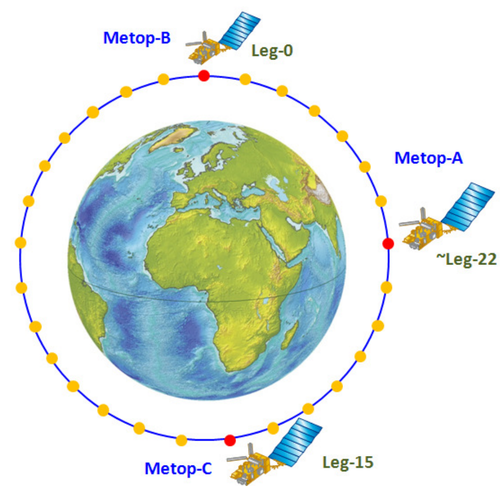

Fig. 12: Metop-A/B/C nominal Trident configuration

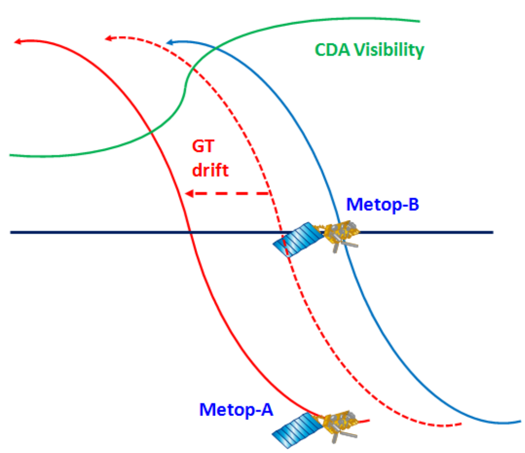

Fig. 13: Impact of ground-track drift on ANX to AOS time

However, to operate three satellites so close is not a trivial task, above all for the ground-station constraints mentioned on the previous paragraph; even assuming an accurate phase control for Metop-A (thus reducing significantly the 2 minutes of margins allocated to its LTAN control to ~0.5 minutes), a minimum separation of 26 minutes would be needed, to which around another minute is to be added to take into account the changes in relative time between ANX and AOS caused by the ground-track drift, as shown in Fig. 13; So a total of 27 minutes of nominal separation would be needed, 2.5 more than the 24.5 minutes available.

Several solutions were envisaged to overcome that problem:
a) optimisation of the operations between LOS of a satellite and AOS of the next one, to reduce that time from the above mentioned 8 minutes;
b) reduction of the pass duration itself, re-defining the AOS and LOS events not at 0-deg elevation but at 5 degrees or even more (LOS can be declared as soon the scientific dump is completed, normally 4 minutes after maximum elevation);

c) implement coordinated operations between LTAN maintenance on Metop-B and C and phase maintenance on Metop-A;
d) position Metop-C not on Leg-15, but on Leg-14, still maximising the separation from Metop-B, even if not on Metop-A original location.

An analysis of the ground-station operation put in evidence that several procedures executed after LOS were also repeated before the following AOS, to enhance robustness; however, a statistical analysis showed that the second execution was nearly never used and could therefore be removed, reducing by around 2 minutes the total needed time.

The option of postponing to 5 degrees the AOS event was discarded, as it would have implied an increased risk on the satellite acquisition operations (the earlier the lock on-board is acquired, the higher the probability of successful transition to auto-track before the start of the scientific dump); also the anticipation of the LOS event was discarded, as several S-band tables, needed for satellite monitoring, are dumped after the end of the scientific dump.

The implementation of coordinated LTAN operation were found to be operationally not recommendable, due to the difference in thrusting performances between Metop-C and Metop-B; that would not have permitted to implement for Metop-C an optimal strategy (minimising the inclination corrections), with unacceptable impact on the mission lifetime.

The proposal of considering Leg-14 as target for the Trident configuration was accepted; that, together with a displacement of the Metop-A phase control location between Leg-21 and Leg-22, permits to gain more than 1.5 minutes of margin, making feasible, with margins, this configuration, shown in Fig. 14.

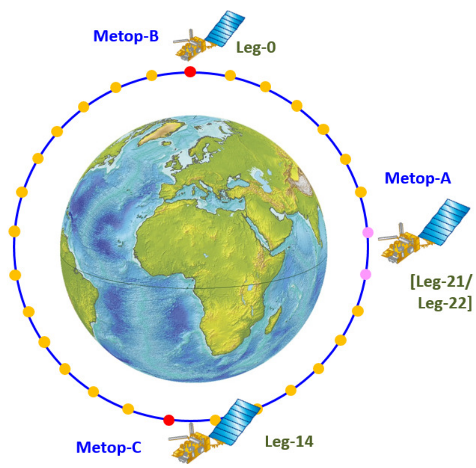

Fig. 14: Metop-A/B/C alternative Trident configuration

However, that does not imply that the Trident will be at the end implemented, as, from an operational point of view, the option of keeping Metop-A, B and C more or less equidistant in phase (so with Metop-C kept on Leg-10 and Metop-A controlled in phase between Leg-19 and Leg-20) is clearly the most robust.

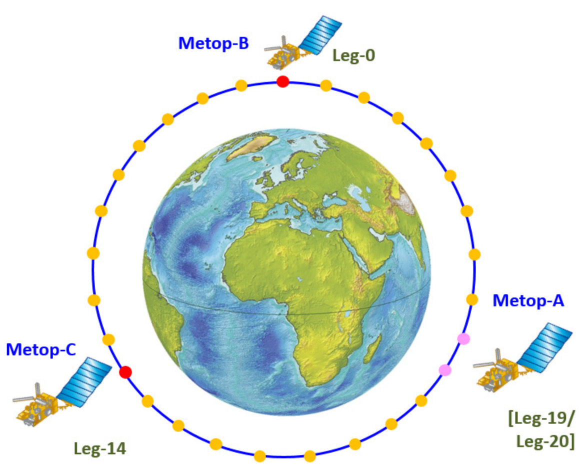

Fig. 15: Metop-A/B/C Tristar configuration

Besides, that option, called Tristar (in Fig. 15) permit not to move Metop-C at the end of the commissioning, with a not negligible saving in operational load and also in fuel (above all if the re-positioning needs to be executed fast)

It is important also to notice that, in terms of observation of the Earth, the two configurations are not at all identical; considering only the two controlled satellites, Metop-B and Metop-C, it can be observed that the Trident configuration ensure no gap for the nadir pointing optical instruments (GOME, even with one satellite in full swat, the other in high resolution swat), while large gaps are observed for the right/left side pointing instrument (ASCAT), being the left side of a satellite exactly on top of the right side of the other satellite (as shown if Fig. 16).

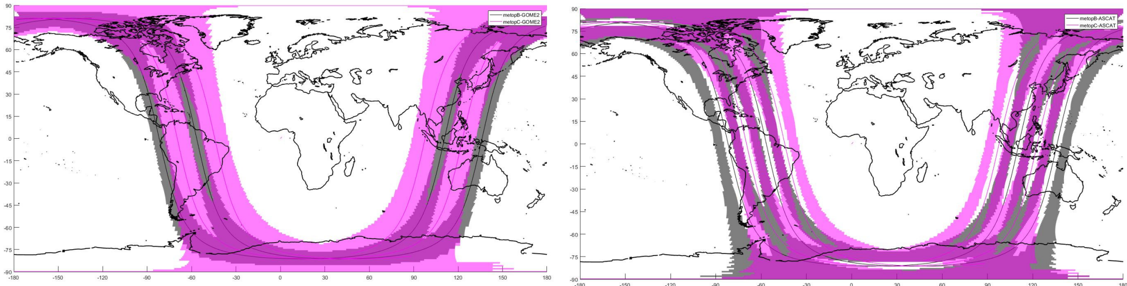

Fig. 16: Coverage figure for Metop-B/C Trident configuration (GOME, ASCAT)

For the Tristar configuration, gaps are observed on the nadir pointing instrument (due to the excessive proximity of the two ground-tracks), while the gap on the right/left side pointing instrument are reduced, as there is no more overlap between right and left side of the two satellites (as shown if Fig. 17).

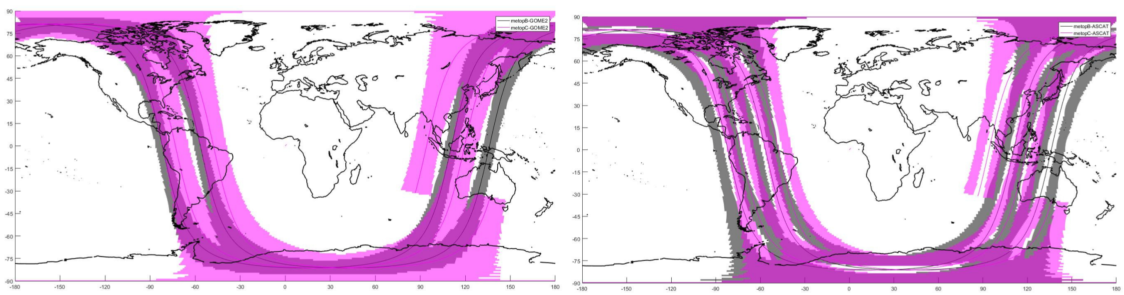

Fig. 17: Coverage figure for Metop-B/C Tristar configuration (GOME, ASCAT)

Metop-A contribution is not considered in that analysis as, being its ground-track uncontrolled (drifting toward Eest), it changes depending on the point in time considered, contributing or not to the coverage depending on the relative position of its ground-track with respect to the one of the two other satellites; the real benefit of Metop-A, regardless of the configuration selected for Metop-C and Metop-B, is that it will fly on an earlier orbit (in terms of LTAN) with respect to the other two satellites.

The decision of which configuration to implement will be taken at the end of the commissioning, also taking into account the observed performances of the Tristar configuration during that period.

Metop-C initial operations

Metop-C was successfully launched on the 7th of November from the Kourou Space Centre by a Soyuz launcher; the achieved orbit was excellent, above all in terms of error in inclination (few millidegrees) and LTAN (few seconds); that permits, as expected, to implement a 1.5 year LTAN cycle without requiring any correction manoeuvre in LEOP; Fig 18 (left) depicts the resulting predicted long term LTAN evolution. Also the error in altitude was moderate (a couple of Km), permitting to reach without any problem Leg-10 around one week after the end of the LEOP, again without requiring any correction during LEOP; Fig 18 (right) present the resulting ground-track (GT) evolution, including the effect of the manoeuvres executed by EUMETSAT first to slow down the drift and then acquire the operational orbit (on the 19th).

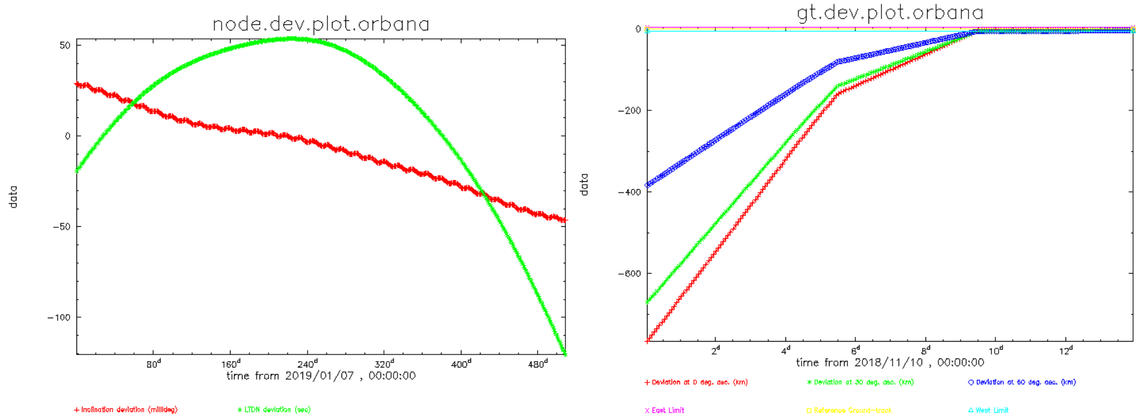

Fig. 18: Metop-C predicted LTAN (long term) and actual GT (to target) evolution

At the date of publishing that paper, no decision was yet taken regarding the final operational location of Metop-C after commissioning.

Conclusions

That paper present the analysis performed by EUMETSAT in support to the preparation of the Metop-C mission, namely to select:
- the best launch time to maximise the probability of not having to perform any inclination correction during the first year of operation;
- the launch date to avoid the risk of interference during critical LEOP phases between Metop-C and one of the already flying Metop satellites;
- the best commissioning location, permitting to implement a robust acquisition strategy, taking into account the constraints imposed by the ground-stations;
- the best operational location, to maximise the scientific return.

The excellent results of the Metop-C initial operations, executed in November, demonstrated the validity of the performed analysis.

Acknowledgment

The author would like to thanks the ESOC Metop-C LEOP team for the excellent work performed, to give us a new space toy to add to our collection.

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